Suppression of Voltage Violation in PV Connected Distribution System via Cooperation of Battery Energy Storage System and SVR

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Abstract—Nowadays, considering of environment protection, Photovoltaic (PV) is well developed in Japan and widely installed in distribution system. However, with the growth of PV, the voltage fluctuation caused by PV can’t be ignored. Because PV totally relies on insolation which is variable and difficult to be predicted. Therefore, voltage profile in distribution system becomes complex and hard for regulation. The established devices in PV connected distribution system is insufficient when deal with the voltage fluctuation. Because the delay in operation and inflexible control ability leads to the voltage violation. Battery Energy Storage System (BESS) is applied to suppress the voltage fluctuation because it can provide the system with immediate, accurate and flexible control. Moreover, the feature of energy storage increases the efficiency of PV. However, cost is the biggest problem in BESS application. To promote the application of BESS, authors focus on two points. One is to realize the application of small-scale BESS. Step Voltage Regulator (SVR) is cooperated with BESS in voltage regulation and makes BESS focuses on the instantaneous voltage. The other is initiative State of Charge (SOC) management. Initiative SOC management realizes more excellent management of charge level in BESS, and it prolongs the lifetime of battery to increase the efficiency in BESS application. In this way, small-scale and long lifetime BESS realizes the economic and excellent control of voltage violation in PV connected distribution system.

Keywords: voltage violation suppression, BESS, SVR, cooperation control, distribution system

I. INTRODUCTION

With the concern of environment and the limit of traditional power resources, nowadays, renewable energy like PV, Wind Farm (WF) is under well development. In Japan, PV is widely applied in distribution system like roof solar. However, with the growth of PV, the voltage violation caused by PV becomes notable. Because PV totally relies on insolation which is variable and can’t be accurately predicted, the voltage profile becomes complex and difficult to control. The voltage suppression in PV connected distribution system is in urgent situation, as in [1]-[3]. To solve the problem of voltage control, the established voltage regulation devices like SVR, Load Ratio Control Transformer (LRT) become insufficient. Because the long settle time and inflexible control ability can’t perfectly deal with the complex voltage profile caused by PV. Therefore, Power Conditioning System (PCS) is here in distribution system to give more excellent control. Such as Static Var Compensator (SVC), it can provide the system with immediate, accurate, and flexible control, as in [4]-[5]. However, cost is the obstacle in its application, and it only gives reactive power output which makes it not always the best choice for voltage control.

BESS with excellent control ability and the unique feature of energy storage draws authors’ attention in voltage control. BESS provides both active and reactive power to system, and it is more serviceable for voltage control. Moreover, with the development Home Energy Management System (HEMS) and Electric Vehicle (EV) shown in [6]-[7], the battery in them is the potential backup of BESS. Therefore, the application method of BESS is urgent to be realized. A lot of study is done around BESS in prior work to promote its application. In [8] and [9], to increase the efficiency of established devices, BESS is cooperated with SVR and LRT in demand response for voltage control. And the limit output of BESS with consideration its capacity is discussed. In [10], State of Charge (SOC) of BESS is discussed. Because SOC is the index in the management of battery’s lifetime in BESS. SOC management of BESS keeps the charge level of battery in proper range. Therefore, battery is protected from overcharge/discharge. In [11], BESS deals with the voltage fluctuation caused by PV, with the active and reactive power from BESS, voltage in distribution system is regulated in proper range. And moreover, based on SOC management, the better charge level of battery is discussed in [12], a relatively long lifetime of battery is realized.

In this paper, authors focus on the voltage violation suppression in PV connected distribution system. And BESS is applied in dealing with voltage violation caused by PV. Moreover, BESS can absorb the reverse power flow caused by PV, and it increases the efficiency of power utilization. However, in the application of BESS, cost is the biggest obstacle. To promote the application of BESS, two points is proposed by authors. One is to realize the application of BESS with small-scale, and the other is to prolong the lifetime of battery in BESS.

For the application of small-scale BESS, the cooperation of BESS and SVR is proposed. SVR cooperates with BESS to solve the long-term voltage violation. BESS only deals with the transient voltage violation, in this way, voltage control with small-scale BESS is realized. Moreover, the
delay of SVR operation is solved by BESS. For the other point, initiative SOC management is proposed. SOC management is operated in no voltage violation period to make more available capacity for voltage control. With the cooperation of BESS and SVR and initiative SOC management, small-scale BESS and long lifetime battery realizes the high efficiency and economic application of BESS. And in this way, the cost in BESS application is relatively reduced.

In section 2, the cooperation control of BESS and SVR in voltage regulation is described; in section 3, simulation and results is shown; and finally in section 4, conclusion is presented.

II. COOPERATION OF BESS AND SVR

To realize the difficult voltage control in PV connected distribution system, BESS is applied because it can provide the system with fast, accurate, and soft control. However, along with the highlight of BESS, the cost of BESS prevents its large-scale application. To reduce the cost, small-scale BESS is wanted and SVR is cooperated with BESS to realize voltage control. The other element of cost reduction is to prolong the lifetime of battery in BESS. Different from prior work, in this paper, initiative SOC management is proposed to protect battery from overcharge/discharge as well as makes more available capacity for voltage control. The cooperation of BESS and SVR realizes the application of small-scale and long lifetime BESS for cost reduction.

A. Control of SVR and BESS in cooperation

In distribution system, SVR regulates the voltage to keep it in adequate range. However, with the growth of PV, SVR can’t perfectly deal with the complex voltage profile in distribution system. Because SVR as Fig.1 shown realizes voltage control through tap change which needs settle time to realize its operation. In Fig. 2, the grey part shows the voltage violation during SVR settle time. To suppress the voltage violation in settle time, BESS gives immediate output. The operation time of SVR is requested by BESS to solve the long-term voltage violation.

In this paper, different from the previous studies which take time or BESS’s inverter capacity as a constraint of SVR’s operation command, the proposed cooperation of SVR and BESS is based on possible voltage violation caused by PV. The preserved capacity of BESS takes the necessary output for voltage violation suppression during SVR settle time as reference. Therefore, with the excellent voltage control of BESS, the utilization of it increases by avoiding the unnecessary preserved capacity during the cooperation with SVR. For fast power flow calculation, the method in [13] is applied.

In Fig. 3, the model of distribution system is shown. SVR and BESS are set in the distribution line. P and Q is load consumption. Z is impedance of distribution line.

\[ \Delta V_n = V_n - V_{ade} \]  
\[ I_B = \frac{\Delta V_n}{\sum Z_j} \]  
\[ S_B = \tilde{V}_{ade} * I_B \]  
\[ S_B = V_{ade} * \left( \frac{\Delta V_n}{\sum Z_j} \right)^* \]  
\[ S_B = \Delta V_n^2 + \Delta V_n \left( \frac{\tilde{V}_n}{\sum Z_j} \right)^* \]  

Fig. 3 Distribution system model with SVR and BESS

The voltage regulation of node n is taken as an example. \( V_n \) is the voltage of node n; \( V_{ade} \) is the reference voltage of its adequate range. When \( V_n \) runs out of its adequate range, BESS firstly gives the immediate control. BESS is taken as current resource. (1)-(4) show the apparent power calculation of BESS. \( I_B \) is current output of BESS; \( \tilde{S}_B \) is apparent power of BESS.

The lifetime of battery is an important index of cost reduction. And SOC management protects battery from overcharge/discharge. In the application of BESS, active power output of BESS directly connects with SOC calculation. Therefore, according to (4), the active power \( P_B \) of BESS is shown in (6). And SOC of BESS is shown in (7). Ts and To are start and stop time of BESS operation.
\[ P_B = \text{real}(V_{ad} * \left( \frac{\delta n}{C_t \cdot r} \right)) \]  
(6)

\[ \text{SOC} = \int_{T_S}^{T_o} P_B \]  
(7)

In distribution system, voltage profile varies with PV. The voltage violation caused by reverse power flow gets the maximum value in sunny day. The case of BESS active power output in sunny day \( P_{Bunny} \) is taken as reference. To solve the delay of SVR operation, BESS needs to provide output for voltage control during settle time of SVR. Therefore, the capacity of BESS for voltage control in settle time need to be ensured. Because SOC management limits the output of BESS, SOC becomes the index for the available capacity of BESS in settle time. Td is settle time of SVR. Based on (7), SOC variation in Td, SOC\_Td is shown in (8). In (8), \( P_{Bunny} \) is applied in SOC calculation, and the available capacity of BESS calculated according to (8) can deal with all cases voltage violation in settle time. And (9) shows the updated SOC\_ref of BESS. t is sample time.

\[ \text{SOC\_Td} = \sum P_{Bunny} \cdot Td \]  
(8)

\[ \text{SOC\_ref}(t) = \text{SOC}(t) + \text{SOC\_Td} \]  
(9)

After arrangement, SOC\_ref is shown in (10). The first part in (10) is the variation of SOC for voltage control. The second part is the predict SOC variation of BESS in settle time of SVR.

\[ \text{SOC\_ref}(t + Td) = \int_{T_S}^{t} P_B + \int_{t}^{t+Td} P_{Bunny} \]  
(10)

According to (10), the updated SOC is calculated. And SVR operation is decided through (11).

\[ \{ \begin{align*} 
\text{Tap} & = 1 \quad \text{if} \quad \text{SOC\_ref} < \text{SOC\_lowerlimit} \\
\text{Tap} & = 0 \quad \text{if} \quad \text{SOC\_lowerlimit} < \text{SOC\_ref} < \text{SOC\_upperlimit} \\
\text{Tap} & = -1 \quad \text{if} \quad \text{SOC\_ref} > \text{SOC\_upperlimit}
\end{align*} \]  
(11)

In (11), if SOC\_ref is lower than its lower limit SOC\_lowerlimit, SVR takes one tap up to increase the voltage. If SOC\_ref is in its adequate range, SVR keeps its state. If SOC\_ref runs larger than its upper limit SOC\_upperlimit, SVR takes one step up to decrease voltage. SOC of BESS is always measured. And according to the rules in (11), BESS sent the request to SVR.

The proposed control method of cooperation between BESS and SVR in this section realizes voltage violation in SVR operation. And the request of SVR operation based on PV’s output avoids unnecessary preserved capacity of BESS for high utilization.

**B. Initiative SOC management in cooperation**

In the application of BESS, SOC management realizes the long lifetime of battery in BESS. And the long lifetime of battery brings the high efficient and low cost of BESS application. The previous studies on SOC management mainly regulate SOC to keep it in its adequate range. However, during voltage suppression, when SOC runs to its boundary, BESS stops its operation unless the voltage violates its opposite limit. Hence, for small-scale BESS, there is always a non-operation period and in this way, it can’t make sure all voltage violation suppression, taking the voltage violation when one more step change of SVR is needed as an example. Considering of increasing the efficiency of BESS, the novelty of proposed SOC management is to make more available capacity of BESS in voltage control. And it is divided into two cases considering of PV’s output. Through initiative charge/discharge of BESS, proposed SOC management realizes variation of available capacity of BESS for voltage control.

Because cost of BESS is the largest obstacle in its application, BESS with small-scale is wanted for cost reduction. In Fig. 4, the voltage profile in distribution line is illustrated. The red part is voltage violation caused by reverse power of PV. To suppress the voltage, BESS provides the immediate control. However, with small-scale BESS, the voltage control with SOC management leads to an unacceptable results as Fig. 5 shows. In Fig. 5(a), SOC runs out of its adequate range for voltage suppression, while Fig. 5(b) shows voltage violation with SOC management of BESS. To make the available capacity of BESS as much as possible, the initiative charge/discharge of BESS is proposed. And it is divided into two cases.

[case 1] 0 < t < Tp

Here, the intensity of solar radiation is \( R_s \). With the variation of \( R_s \), voltage profile is different. According to the voltage profile in sunny day, the maximal voltage \( V_{max} \) caused by PV’s reverse power flow is got, and the time of
peak output of PV is $T_p$. Before $T_p$, BESS always operates
initiative discharge to make more available capacity for
reverse power flow. With the same example in Fig. 3, based
on (6), (12) shows the initiative discharge of BESS.
$V_{\text{upper limit}}$ is the upper limit of voltage and $w$ is the weight
coefficient. $S_{\text{OC,ini}}$ is SOC variation during period, $T_{\text{ini}}$, of
initiative discharge. and (13) shows the calculation.

$$
P_B = \text{real}(V_{\text{upper limit}} \ast w \ast \left(\frac{V_n - V_{\text{upper limit}}}{\Sigma \delta_j}\right))
$$

(12)

SOC_{ini}(t) = \sum P_B \ast T_{\text{ini}}

(13)

With SOC_{ini}, the updated state of charge SOC_m is shown
in (14). $\alpha$ and $\beta$ are weight coefficient.

$$
SOC_m(t) = \alpha \ast SOC(t) + \beta \ast SOC_{\text{ini}}
$$

(14)

When $R_s$ is larger than its reference value $\gamma$, the output
of PV has high probability to increase the voltage. The
operation of initiative SOC management is based on (15).

$$
\left\{ \begin{array}{l}
\alpha = 0 \text{ and } \beta = 1 \\
\text{if } V_{\text{lower limit}} < V_n < V_{\text{upper limit}} \\
\alpha = 1 \text{ and } \beta = 0 \\
\text{if } V_{\text{upper limit}} < V_n
\end{array} \right.
$$

(15)

And when $R_s$ is smaller than its reference value $\gamma$, (16)
shows the operation of SOC management.

$$
\left\{ \begin{array}{l}
\alpha = 0 \text{ and } \beta = 0 \\
\text{if } V_{\text{lower limit}} < V_n < V_{\text{upper limit}} \\
\alpha = 1 \text{ and } \beta = 0 \\
\text{if } V_{\text{upper limit}} < V_n
\end{array} \right.
$$

(16)

III. SIMULATION AND RESULTS

A. Simulation conditions

Fig.6 gives the detail model of distribution system which
has 21 loads with PV. In this model, BESS is set as current
resource. PV’s factor is equal to 1.0 and just provides
the system with active power. And the verification is realized by
MATLAB through power flow calculation.

The green arrows stand for three-phase loads. The blue
arrows stand for single-phase loads that are residential load.
PVs are connected at the same placement of single-phase
loads, PV in sunny day is selected as the reference and PV in
cloudy day is chosen to verify the suppression of voltage
fluctuation.

BESS is set at the end of distribution line and SVR is set in
the middle of distribution line to verify the cooperation of
BESS and SVR. Table 1 shows the parameters. Table 2 shows
the single-phase load’s placement.

<table>
<thead>
<tr>
<th>Impedance of distribution line</th>
<th>A132:0.899 + j0.389Ω/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A158:0.497 + j0.331Ω/km</td>
</tr>
<tr>
<td></td>
<td>A195:0.301 + j0.315Ω/km</td>
</tr>
<tr>
<td></td>
<td>A1200:0.182 + j0.288Ω/km</td>
</tr>
<tr>
<td>Total length of the line</td>
<td>3.09/km</td>
</tr>
</tbody>
</table>

| Table 1. Distribution line’s data. |

<table>
<thead>
<tr>
<th>Connection phase</th>
<th>Load No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-b</td>
<td>3, 8, 15, 21</td>
</tr>
<tr>
<td>b-c</td>
<td>4, 10, 17, 20</td>
</tr>
<tr>
<td>c-a</td>
<td>7, 14</td>
</tr>
</tbody>
</table>

| Table 2. Connection of single-phase load. |

The pattern of three-phase loads is illustrated in Fig.7 and
consumption is 125kW of each one. Fig.8 shows the load pattern of single-phase load which ranges from 108kW to 648 kW. Fig.9 illustrated the output in cloudy day. The capacity
of PV equals to the maximum single-phase load consumption.
All of them are given in proportion.

![Fig. 7 Three-phase load’s pattern](image)
The time step of the simulation is 1 min. The adequate range of line voltage is from 101 to 107 conversed to low voltage side using voltage ratio (≈ 6600/105). In Table 3 gives the simulation conditions.

<table>
<thead>
<tr>
<th>Table 3. Simulation conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time</td>
</tr>
<tr>
<td>Simulation interval</td>
</tr>
<tr>
<td>Adequate range’s V\text{upper limit}</td>
</tr>
<tr>
<td>Adequate range’s V\text{lower limit}</td>
</tr>
<tr>
<td>Ratio of voltage</td>
</tr>
<tr>
<td>Sending voltage of substation</td>
</tr>
<tr>
<td>BESS capacity</td>
</tr>
<tr>
<td>State of charge’s SOC\text{upper limit}</td>
</tr>
<tr>
<td>State of charge’s SOC\text{lower limit}</td>
</tr>
<tr>
<td>Initial SOC</td>
</tr>
<tr>
<td>One tap of SVR</td>
</tr>
<tr>
<td>Capacity of battery</td>
</tr>
</tbody>
</table>

Table 4 shows the simulation cases. Case 1 is the original distribution system without BESS and SVR, and it is taken as a reference case. Case 2 has BESS and SVR without cooperation and initiative SOC management in voltage control. The cooperation of BESS and SVR is done in case 3 without the initiative SOC management to make a comparison. Case 4 discusses the proposed cooperation of BESS and SVR with initiative SOC management.

<table>
<thead>
<tr>
<th>Table 4. Simulation cases.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
</tr>
<tr>
<td>Case 2</td>
</tr>
<tr>
<td>Case 3</td>
</tr>
<tr>
<td>Case 4</td>
</tr>
</tbody>
</table>

In Fig. 10, the voltage profile of node 21 where has the severe voltage violation is illustrated. It can be seen that voltage runs out of its adequate range with the reverse power flow caused by PV. Here, in this paper, authors select the period from 10am to 12pm as Fig. 11 shows to verify the proposed method in suppression of voltage violation caused by PV.

In Fig. 12, the voltage profile in case 2 is illustrated. BESS gives the immediate control to suppression the voltage.
However, for long-term voltage regulation, without the proposed cooperation, voltage violation in settle time of SVR appears in the dashed box. In Fig. 13, SOC of BESS is well control in its adequate range.

Fig. 16 shows the result of voltage suppression with proposed method and initiative SOC management. It can be seen that the voltage is well controlled. With the proposed method, the application of BESS with small-scale is realized. Compared with case 3, the initiative SOC management provides more alternative capacity of BESS for voltage control as shown in Fig. 17.

IV. CONCLUSIONS

In this paper, the suppression of voltage violation is discussed. The cooperation of BESS and SVR is proposed and verified by MATLAB. With the proposed method, two points is conducted.

1). With the assistance of SVR, comparing with large-scale BESS, the application of small-scale BESS with relatively low cost is realized. And preserved capacity of BESS for voltage suppression in SVR’s settle period is calculated based on PV’s output. Hence, unnecessary preserved capacity of BESS is avoided.

2). The initiative SOC management is proposed. The novelty of the proposed strategy provides much more available capacity for voltage control and increases the efficiency of BESS via decreasing its non-operation period.

For future study, to realize more excellent voltage control, more severe cases in PV connected distribution system need to be discussed. The predict of voltage profile in PV connected distribution system is also wanted for more accurate control. Moreover, the details in initiative SOC management is wanted to prolong the lifetime of battery for high efficiency and economic application of BESS.

V. REFERENCE

